CHAPTER 5

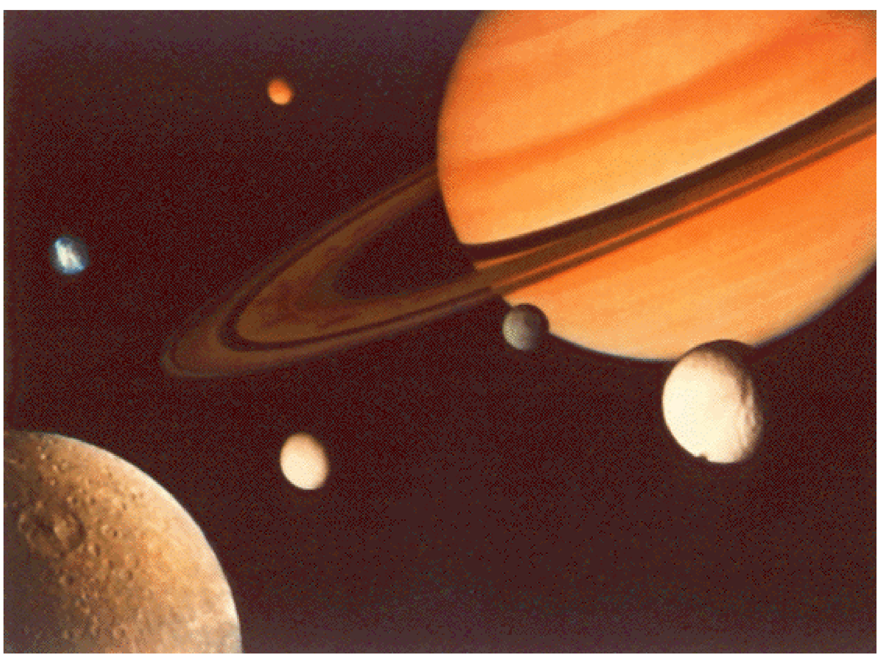
The Icy Satellites

The moons, or satellites, of Saturn represent a diverse set of objects. They range from the planet-like Titan, which has a dense atmosphere, to tiny, irregular objects only tens of kilometers in diameter. These bodies are all believed to have as major components some type of frozen volatile, primarily water ice, but also other components such as methane, ammonia and carbon dioxide existing either alone or in combination with other volatiles. Saturn has at least 18 satellites; there may exist other small, undiscovered satellites in the planet's system.

Overall Characteristics

In 1655, Christiaan Huygens discovered Titan, the giant satellite of Saturn. Later in the 17th century, Jean-Dominique Cassini discovered the four next largest satellites of Saturn. It was not until more than 100 years later that two smaller moons of Saturn were discovered. As telescopes acquired more resolving power in the 19th century, the family of Saturn's satellites grew.

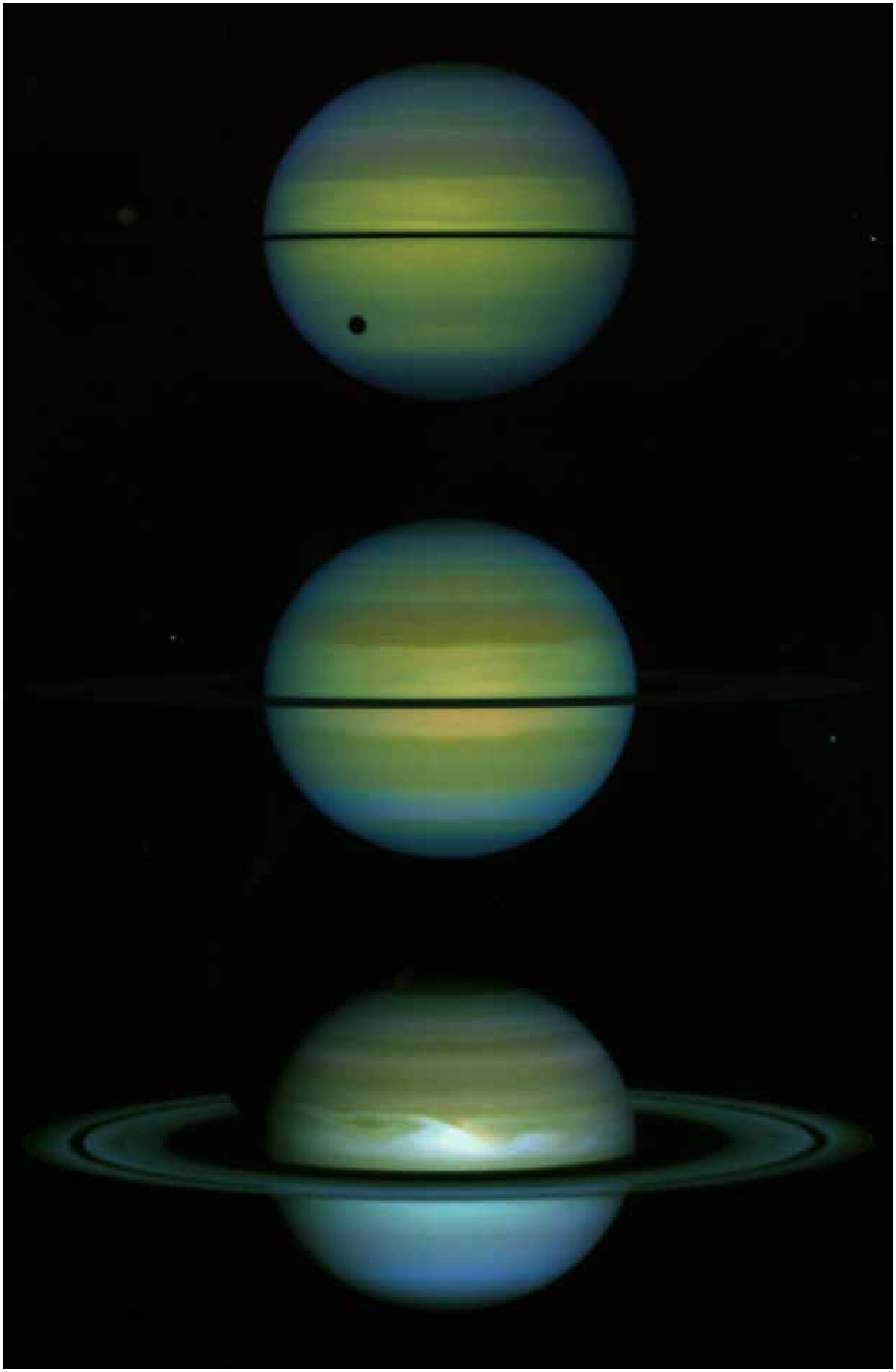
Most of the smallest satellites were discovered during the Voyager spacecraft flybys. The 18th satellite, Pan, was found nearly 10 years after the flybys during close analysis of Voyager images; it is embedded in the A-ring of Saturn. Saturn's ring plane crossings — when the obscuring light from Saturn's bright rings dims, as the rings move to an edge-on orientation — represent the ideal configuration for discovering new satellites. Images obtained by the Hubble Space Telescope during the ring plane crossings in 1995 did not reveal any unambiguous discoveries of new satellites.



The satellites of Saturn comprise a diverse set of objects. This composite image shows, from top, Mimas, Rhea, Iapetus, Tethys, Enceladus and Dione.

Physical and Dynamic Properties

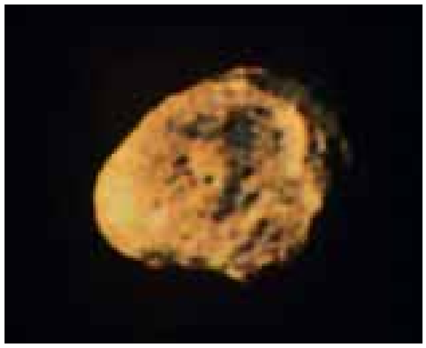
Most planetary satellites present the same hemisphere toward their primaries, a configuration that is the result of tidal evolution. When two celestial bodies orbit each other, the gravitational force exerted on the near side is greater than that exerted on the far side. The result is an elongation of each body that forms tidal bulges, which can consist of either solid, liquid or gaseous (atmospheric) material. The primary tugs on the satellite's tidal bulge to lock its longest axis on to the primary satellite line. The satellite, which is said to be in a state of synchronous rotation, keeps the same face toward the primary. Since this despun state occurs rapidly (usually within a few million years), most natural satellites are in synchronous rotation. Of Saturn's icy satellites, two, Hyperion and Phoebe, are known to exhibit asynchronous rotation.



The Hubble Space Telescope obtained these images of Saturn and its rings and satellites. The top image, obtained in August 1995, shows Titan (far left, casting a shadow) and (far right, from the left), Mimas, Tethys, Janus and Enceladus. In the middle image, obtained in November 1995, Tethys (upper left) and Dione appear. In the bottom image, obtained in December 1994, a storm is raging in the center of the planet. [Images courtesy of: top and middle — E. Karkoschka, University of Arizona Lunar and Planetary Laboratory; bottom — R. Beebe, New Mexico State University]

Before the advent of spacecraft exploration, planetary scientists expected the satellites of the outer planets to be geologically dead. They assumed that heat sources were not sufficient to have melted the satellites' mantles enough to provide a source of liquid or even semiliquid ice or ice silicate slurries. The Voyager and Galileo spacecraft have radically altered this view by revealing a wide range of geological processes on the moons of the outer planets. Enceladus may be currently active. Several of Saturn's medium-sized satellites are large enough to have undergone internal melting with subsequent differentiation and resurfacing.

Recent work on the importance of tidal interactions and subsequent heating has provided the theoretical foundation for explaining the existence of widespread activity in the outer solar system. Another factor is the presence of non-ice components, such as ammonia hydrate or methane clathrate, which lower the melting points of near-surface materials. Partial melts of water ice and various contaminants — each with their own melting point and viscosity — provide material for a wide range of geological activity.



Hyperion is an irregular, pockmarked satellite in an unusual, nonsynchronous rotational state.

Because the surfaces of so many outer planet satellites exhibit evidence of geological activity, planetary scientists have begun to think in terms of unified geological processes occurring on the planets — including Earth — and their satellites. For example, partial melts of water ice with various contaminants could provide flows of liquid or partially molten slurries that in many ways mimic the terrestrial or lunar lava flows formed by the partial melting of silicate rock mixtures. The ridged and grooved terrains on satellites such as Enceladus and Tethys may have resulted from tectonic activities occurring through-

THE KNOWN MOONS OF SATURN

Moon	Diameter, kilometers	Distance, kilometers	Orbital Period, days	Year Discovered: Discoverer
Pan	20	133,580	0.56	1990: Showalter
Atlas	30	137,670	0.60	1980: Terrile
Prometheus	100	139,350	0.61	1980: Collins
Pandora	90	141,700	0.63	1980: Collins
Epimetheus	120	151,450	0.69	1966: Walker
Janus	190	151,450	0.69	1966: Dolfus
Mimas	392	185,520	0.94	1789: Herschel
Enceladus	500	238,020	1.37	1789: Herschel
Tethys	1060	294,660	1.89	1684: Cassini
Telesto	30	294,660	1.89	1980: Smith
Calypso	26	294,660	1.89	1980: Smith
Dione	1120	377,400	2.74	1684: Cassini
Helene	32	377,400	2.74	1980: Laques and Lecacheux
Rhea	1530	527,040	4.52	1672: Cassini
Titan	5150	1,221,830	15.94	1655: Huygens
Hyperion	290	1,481,100	21.28	1848: Bond
Iapetus	1460	3,561,300	79.33	1671: Cassini
Phoebe	220	12,952,000	550.40	1898: Pickering

out the solar system. Finally, the explosive volcanic eruptions possibly occurring on Enceladus may be similar to those occurring on Earth, which result from the escape of volatiles released as the pressure decreases in upward-moving liquids.

Formation and Bulk Composition

The solar system — the Sun, the planets and their families of moons — condensed from a cloud of gas and dust about 4.6 billion years ago. This age is derived primarily from radiometric dating of meteorites, which are believed to consist of primordial, unaltered matter. Because there existed a temperature gradient in the protosolar cloud, or nebula, volatile materials (those with low condensation temperatures) are the major components of bodies in the outer solar system. These materials include water ice, ice silicate mixtures, methane, ammonia and the hydrated forms of the latter two materials. Two types of dark contaminants exist on the surfaces of the satellites: C-type or carbon-rich material, and D-type material, which is believed to be rich in hydrocarbons.

The planets and their satellite systems formed from the accretion of successively larger blocks of material, or planetesimals. One important concept of planetary satellite formation is that a satellite cannot accrete within Roche's limit, the distance at which the tidal forces of the primary become greater than the internal cohesive forces of the satellite. Except for Titan, Saturn's satellites are too small to possess gravity sufficiently strong to retain an appreciable atmosphere against thermal escape.

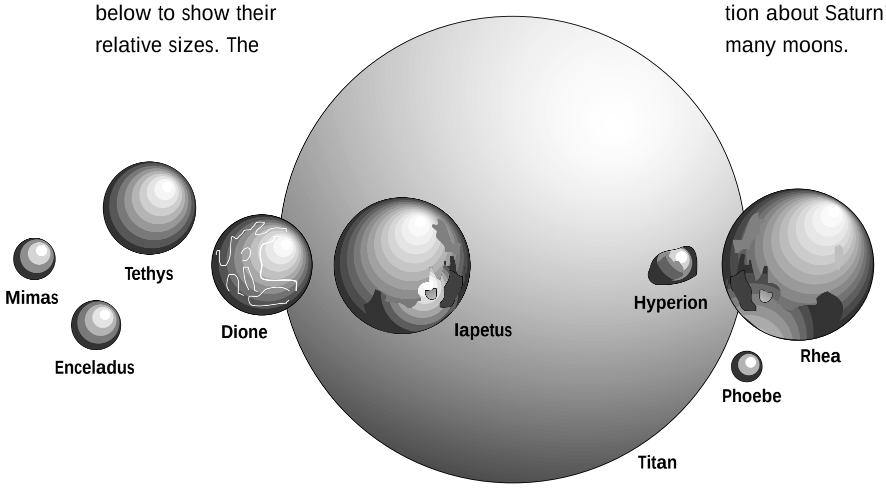
Evolution

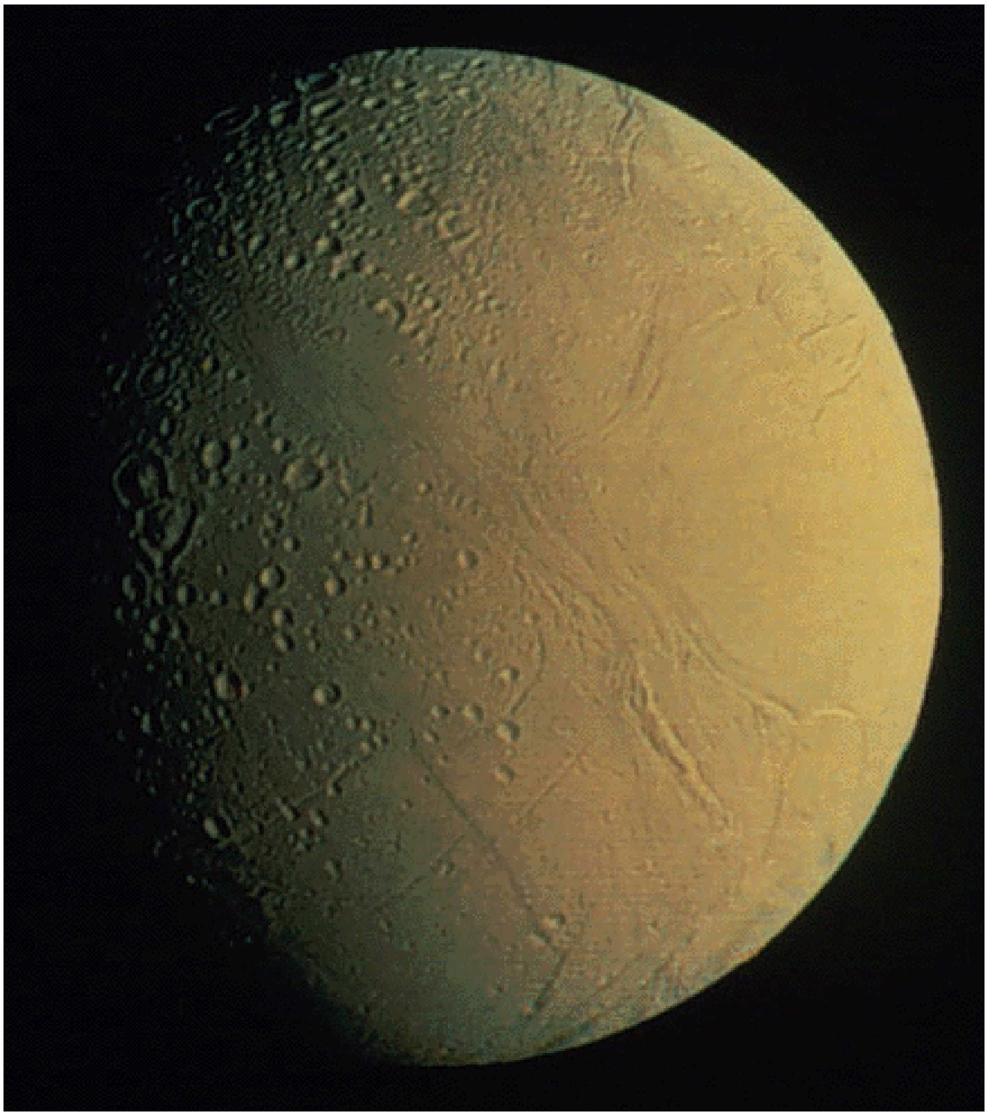
Soon after the satellites accreted, they began to heat up from the release of gravitational potential energy. An additional heat source was provided by the release of mechanical energy during the heavy bombardment of their surfaces by remaining debris. Mimas and Tethys have impact craters (named Herschel and Odysseus, respectively) caused by bodies that were nearly large enough to break them apart; probably such catastrophes did occur. The decay of radioactive elements found in silicate materials provided another major source of heat. The heat produced in the larger satellites may have been sufficient to cause melting and chemical fractionation; the dense material, such as silicates and iron, went to the center of the satellite to form a core, while ice and other volatiles remained in the crust. A fourth source of heat is provided by the release of frictional energy as heat during tidal and resonant interactions among the satellites and Saturn.

Several of Saturn's satellites underwent periods of melting and active geology within a billion years of their formation and then became quiescent. Enceladus may be currently geologically active. For nearly a billion years after their formation, the satellites all underwent intense bombardment and cratering. The bombardment tapered off to a slower rate and presently continues. By counting the number of craters on a satellite's surface and making certain assumptions about the flux of impacting ma-

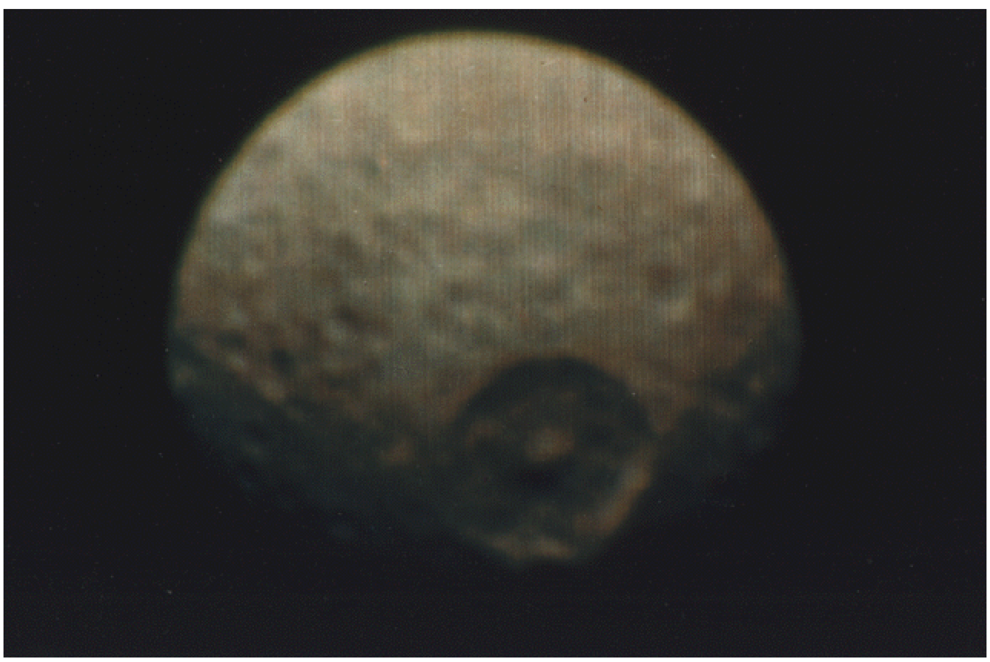
SMALL ONES, BIG ONES...

The moons, or satellites, of Saturn comprise a diverse set of objects. Of the 18 currently known satellites, nine are illustrated below to show their relative sizes. The planet-like Titan is easily the largest of Saturn's moons. It has a dense atmosphere and possibly liquid oceans on its surface. Hyperion, by contrast, is irregularly shaped and seems to be covered with ice and dark, rocky material. The Cassini–Huygens mission, through its detailed observations, will provide us with much more information about Saturn's many moons.





The bright surface of Saturn's moon Enceladus shows evidence of extensive resurfacing over time.



The Herschel crater covers approximately one third of the diameter of the surface on the moon Mimas.

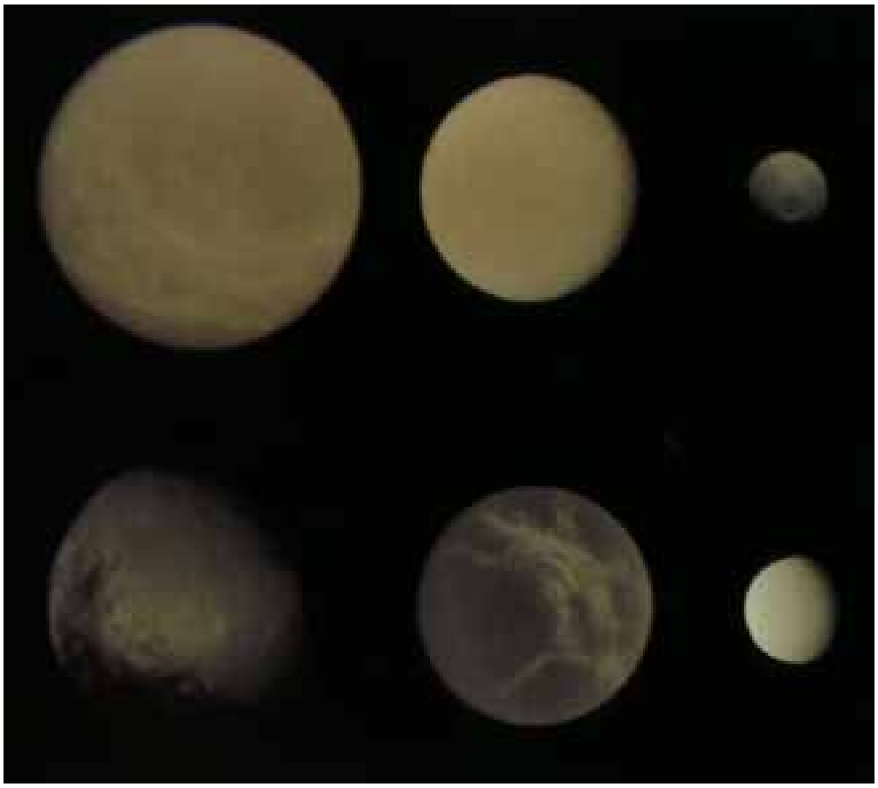
terial, geologists are able to estimate when a specific portion of a satellite's surface was formed. Continual bombardment of satellites causes the pulverization of both rocky and icy surfaces to form a covering of fine material known as a regolith.

Meteoritic bombardment of icy bodies alters the optical characteristics of the surface by excavating and exposing fresh material. Impacts can also cause volatilization and the subsequent escape of volatiles to create a lag deposit enriched in opaque, dark materials. Both the Galilean satellites of Jupiter and the medium-sized satellites of Saturn tend to be brighter on the hemispheres leading in the direction of orbital motion (the so-called "leading" side, as opposed to the "trailing" side); this effect is thought to be due to preferential micrometeoritic "gardening" on the leading side.

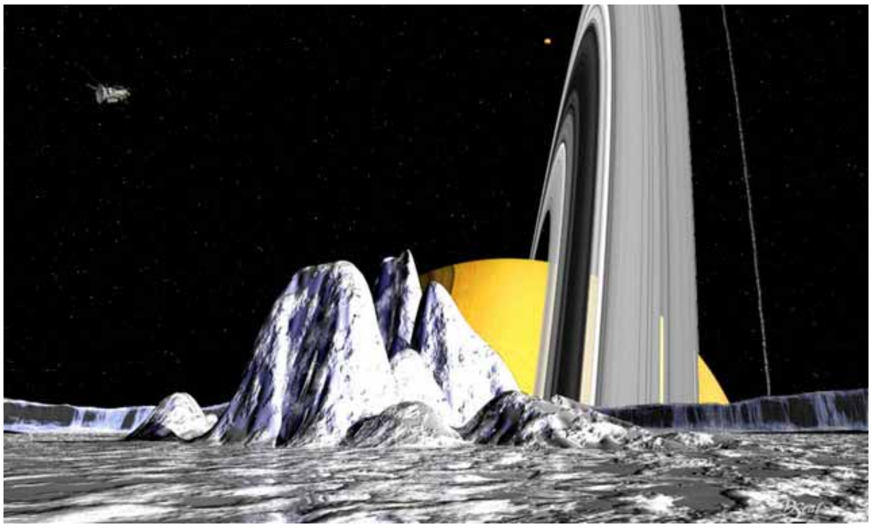
Many geologists expected the craters formed on the outer planets' satellites to have disappeared from viscous relaxation. Voyager images reveal craters that in many cases have morphological similarities to those found in the inner solar system, including central pits, large ejecta blankets and well-formed outer walls. Scientists now believe that silicate mineral contaminants or other impurities in the ice provide the extra strength required to sustain impact structures.

Individual Satellites

Medium-Sized Icy Satellites. These six satellites of Saturn are smaller than Titan and Jupiter's giant Galilean satellites, but they are still sizable — and as such they represent a unique class of icy satellite. Earth-based telescopic measurements showed the spectral signature of ice for Tethys, Rhea and Iapetus; Mimas and Enceladus are close to Saturn and difficult to observe because of scattered light from the planet. The satellites' low densities and high albedos imply that their bulk composition is largely water ice, possibly combined with ammonia or other volatiles. They have smaller amounts of rocky silicates than the



The six medium-sized icy satellites of Saturn. Clockwise from upper left: Rhea, Tethys, Mimas, Enceladus, Dione and Iapetus.



Artist's view of Saturn as seen from the planet's heavily cratered moon, Mimas. In the middle of the image is a central pit of a large impact crater.

Galilean satellites. Most of what is presently known of the Saturn system was obtained from the Voyager flybys in 1980 and 1981.

Saturn's innermost, medium-sized satellite, Mimas, is covered with craters, including one named Herschel that covers a third of the moon's diameter. There is a suggestion of surficial grooves that may be features caused by the impact. The craters on Mimas tend to be high-rimmed, bowl-shaped pits; apparently surface gravity is not sufficient to have caused viscous relaxation. The application of crater-counting techniques to Mimas suggests that it has undergone several episodes of resurfacing.

The next satellite outward from Saturn is Enceladus, an object that was known from telescopic measurements to reflect nearly 100 percent of the visible radiation incident on it (for comparison, Earth's Moon reflects only about 11 percent). The only likely composition consistent with this observation is almost pure water ice or some other highly reflective volatile. Voyager 2 images show an object that had been subjected, in the recent geological past, to extensive resurfacing; grooved formations similar to those on the Galilean satellite Ganymede are prominent.

The lack of impact craters on this terrain is consistent with an age of less than a billion years. Some form of ice volcanism may be currently occurring on Enceladus. A possible heating mechanism is tidal interactions, perhaps with Dione. About half of the surface observed by Voyager is extensively cratered, consistent with an age of four billion years.

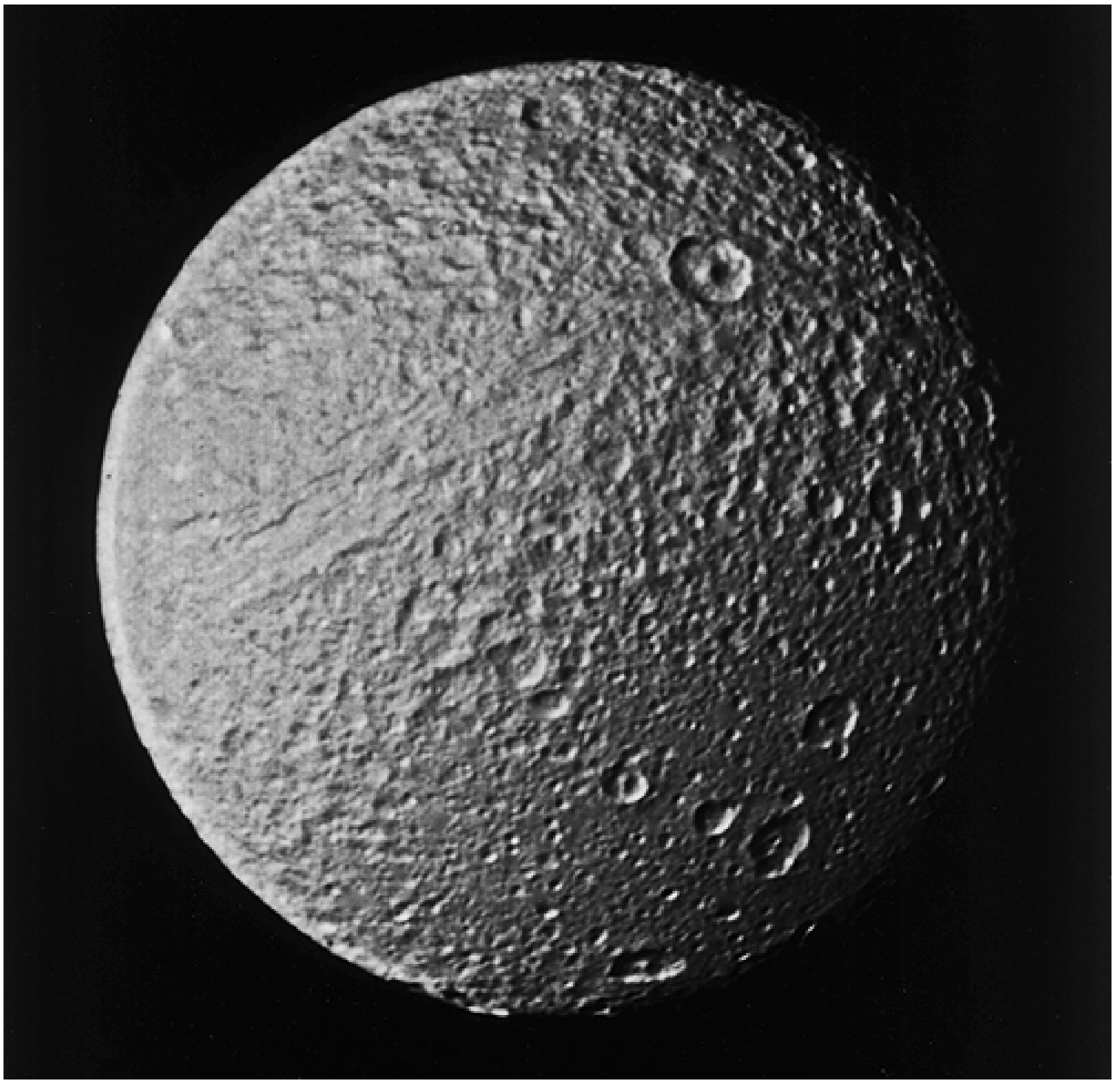
A final element to the puzzle of Enceladus is the possibility that it is responsible for the formation of the E-ring of Saturn, a tenuous collection of icy particles that extends from inside the orbit of Enceladus to past the orbit of Dione. The maximum thickness position of the ring coincides with the orbital position of Enceladus. If some form of volcanism is presently active on the surface, it could provide a source of particles for the ring. An alternative source mechanism is the escape of particles from the surface due to meteoritic impacts.

Tethys is covered with impact craters, including Odysseus, the largest known impact structure in the solar system. The craters tend to be flatter than those on Mimas or the Moon, probably because of viscous relaxation and flow over the eons under Tethys' stronger gravitational field. Evidence for episodes of resurfacing is seen in regions that have fewer craters and higher albedos. In addition, there is a huge trench formation, the Ithaca Chasma, which may be a degraded form of the grooves found on Enceladus.

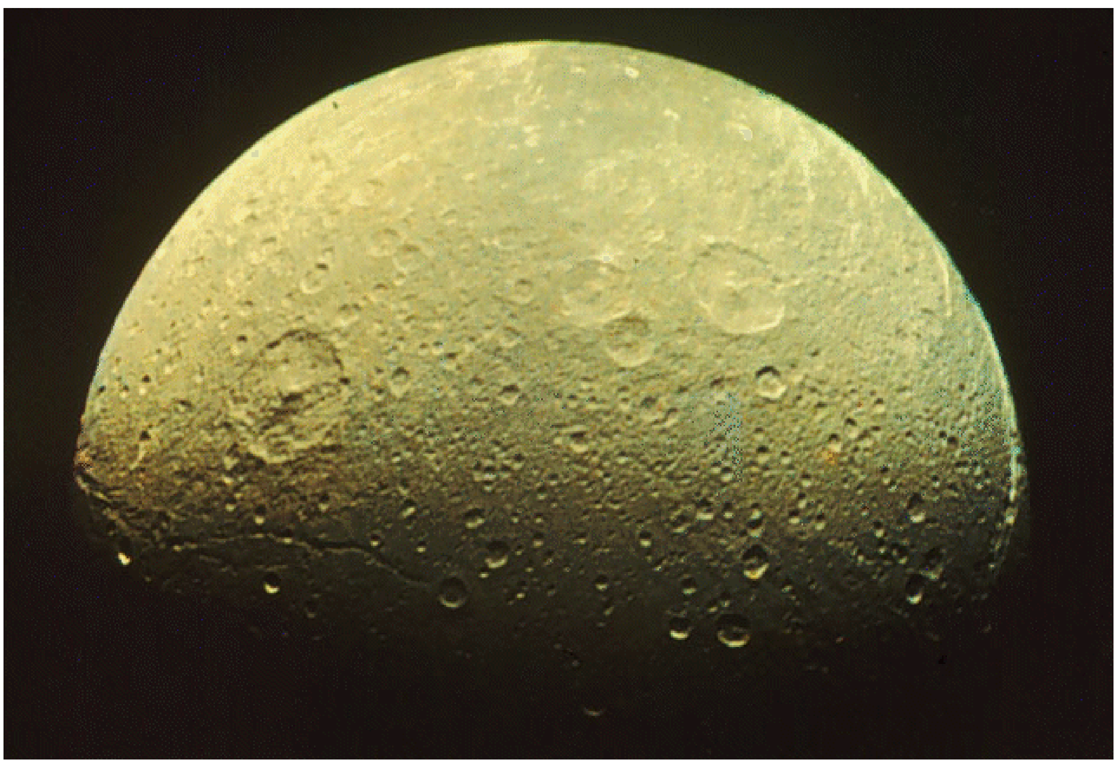
Dione, about the same size as Tethys, but more dense, exhibits a wide diversity of surface morphology. Next to Enceladus, it has the most extensive evidence for internal activity. Its relatively high density may provide added radiogenic heat from siliceous material to spur this activity. Most of the surface is heavily cratered, but gradations in crater density indicate that several periods of resurfacing occurred during the first billion years of its existence. The leading side of the satellite is about 25 percent brighter than the other, due possibly to more intensive micrometeoritic bombardment on this hemisphere. Wispy streaks, which are about 50 percent brighter than the surrounding areas, are believed to be the result of internal activity and subsequent emplacement of erupting material. Dione modulates the radio emission from Saturn, but the mechanism responsible for this phenomenon is unknown.

Rhea appears to be superficially very similar to Dione. Bright wispy streaks cover one hemisphere. However, there is no evidence for any resurfacing events early in its history. There does seem to be a dichotomy between crater sizes — some regions lack large craters while other regions have a preponderance of such impacts. The larger craters may be due to a population of larger debris more prevalent during an earlier episode of collisions. The craters on Rhea show no signs of viscous relaxation.

When Cassini discovered Iapetus in 1672, he noticed almost immediately that at one point in its orbit around Saturn it was very bright, but on the opposite side of the orbit, the moon nearly disappeared. He correctly de-



The cratered surface of Tethys, including the groove-like Ithaca Chasma and the crater Telemachus at the upper right.



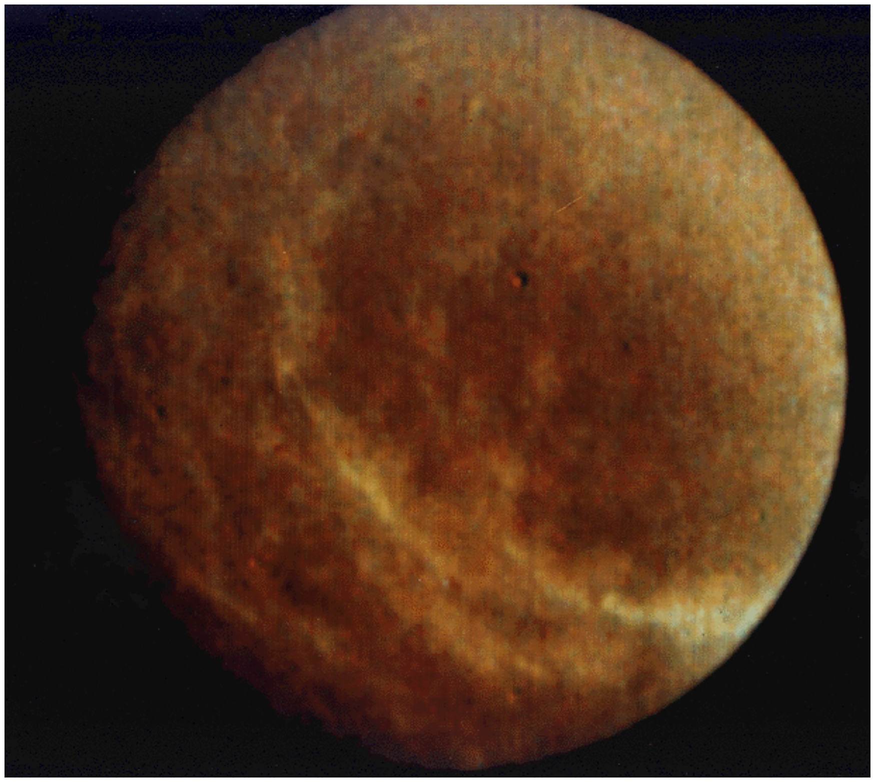
The heavily cratered face of Dione is shown in this Voyager 1 image. Bright wispy streaks are visible on the limb.

duced that one hemisphere is composed of highly reflective material, while the other side is much darker. Voyager images show that the bright side, which reflects nearly 50 percent of the incident radiation, is fairly typical of a heavily cratered icy satellite. The other side, which is centered on the direction of motion, is coated with a redder material that has a reflectivity of about three to four percent.

Scientists do not agree on whether the dark material originated from an exogenic source or was endogenically created. One scenario for the exogenic deposit of material entails dark particles being ejected from Phoebe and drifting inward to coat Iapetus. The major problem with this model is that the dark material on Iapetus is redder than Phoebe, although the material could have undergone chemical changes after its expulsion from Phoebe that made it redder. One observation lending credence to an internal origin is the concentration of material on crater floors, which implies an infilling mechanism. In one model, methane erupts from the interior and is subsequently darkened by ultraviolet radiation.

Other characteristics of Iapetus are odd. It is the only large Saturn satellite in a highly inclined orbit. It is less dense than objects of similar albedo; this fact implies a higher fraction of ice or possibly methane or ammonia in its interior.

Small Satellites. The Saturn system has a number of unique small satellites. Three types of objects have been found only in the Saturn system: the shepherding satellites, the co-orbitals and the Lagrangians. All three groups of satellites are irregularly shaped and probably consist primarily of ice.



An array of bright streaks is visible in this view of Rhea, Saturn's second largest satellite.

The three shepherds, Atlas, Pandora and Prometheus, are believed to play a key role in defining the edges of Saturn's A and F rings. The orbit of Saturn's second innermost satellite, Atlas, lies several hundred kilometers from the outer edge of the A-ring. The other two shepherds, which orbit on either side of the F-ring, constrain the width of this narrow ring and may cause its kinky appearance.

The co-orbital satellites, Janus and Epimetheus, which were discovered in 1966 and 1978, respectively, exist in an unusual dynamic situation. They move in almost identical orbits at about two and a half Saturn radii. Every four years, the inner satellite (which orbits slightly faster than the outer one) overtakes its companion. Instead of colliding, the satellites exchange orbits. The four-year cycle then begins again. Perhaps these two satellites were once part of a larger body that disintegrated after a major collision.

The three other small satellites of Saturn — Calypso, Helene and Telesto — orbit in the Lagrangian points of larger satellites, one associated with Dione and two with Tethys. Lagrangian points are locations within an object's orbit in which a less massive body can move in an identical, stable orbit. The points lie about 60 degrees in front of and behind the larger body. Although no other known satellites in the solar system are Lagrangians, the Trojan asteroids orbit in two of the Lagrangian points of Jupiter.

Telescope observations showed that the surface of Hyperion, which lies between the orbits of Iapetus and Titan, is covered with ice. Because Hyperion has a relatively low albedo, however, this ice must be mixed with a significant amount of darker, rocky material. The color of Hyperion is similar to that of the dark side of Iapetus and D-type asteroids: All three bodies may be rich in primitive material rich in organics. It is darker than the medium-sized, inner satellites, presumably because resurfacing events have never covered it with fresh ice.

Although Hyperion is only slightly smaller than Mimas, it has a highly irregular shape, which along with the satellite's battered appearance, suggests that it has been subjected to intense bombardment and fragmentation. There is also good evidence that Hyperion is in a chaotic rotation, perhaps a collision within the last few million years knocked it out of a tidally locked orbit.

Saturn's outermost satellite, Phoebe, a dark object with a surface composition probably similar to that of C-type asteroids, moves in a highly inclined, retrograde orbit, suggesting it is a captured object. Voyager images show definite variegations consisting of dark and bright (presumably icy)

HOW TO NAME A MOON

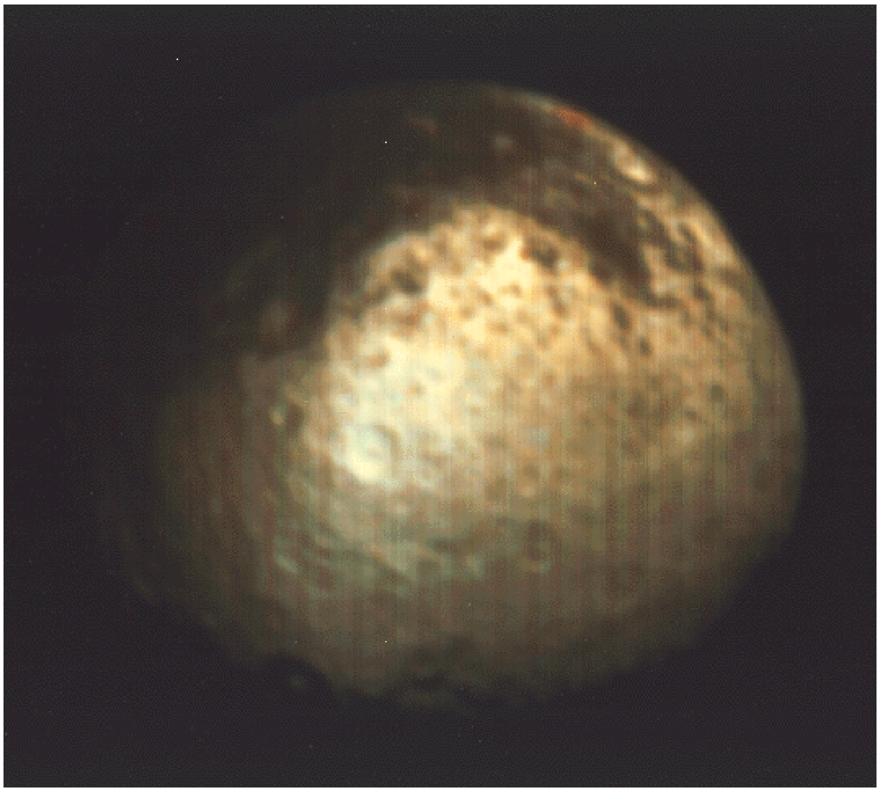
Planetary satellites, including Saturn's, are generally named after figures in classical Greek or Roman mythology associated with the namesakes of their primaries. Hyperion, Iapetus, Phoebe, Rhea and Tethys, for example, were siblings of Kronos, the Greek counterpart of the Roman god Saturn.

The satellites also carry scientific designations, which comprise the first letter of the primary followed by a sequential Arabic numeral, assigned in order of discovery: Mimas is S1, Titan is S2 and so on. When satellites are first discovered, but not yet confirmed or officially named, they are known by the year in which they were discovered, the initial of the primary and a number assigned consecutively for all solar system discoveries. So, Pan was first called 1981S13 (although Pan was discovered in 1990, the Voyager image in which the moon was found was obtained in 1981).

After planetary scientists were able to map geological formations of the satellites from spacecraft images, they named many of the features after characters or locations from world mythologies. The official names for all satellites and surface features are assigned by the International Astronomical Union.

patches on the surface. Although it is smaller than Hyperion, Phoebe has a nearly spherical shape. With a rotation period of about nine hours, Phoebe is the only Saturn satellite known to exhibit a simple, asynchronous rotation.

Pan, the 18th known satellite of Saturn, was discovered in 1990 in Voyager 2 images that were obtained in 1981. This small object is embedded within the A-ring and helps to clear the Encke division of particles.



This Voyager 2 image of Iapetus shows both bright and dark terrains on the moon.

The Cassini–Huygens Mission

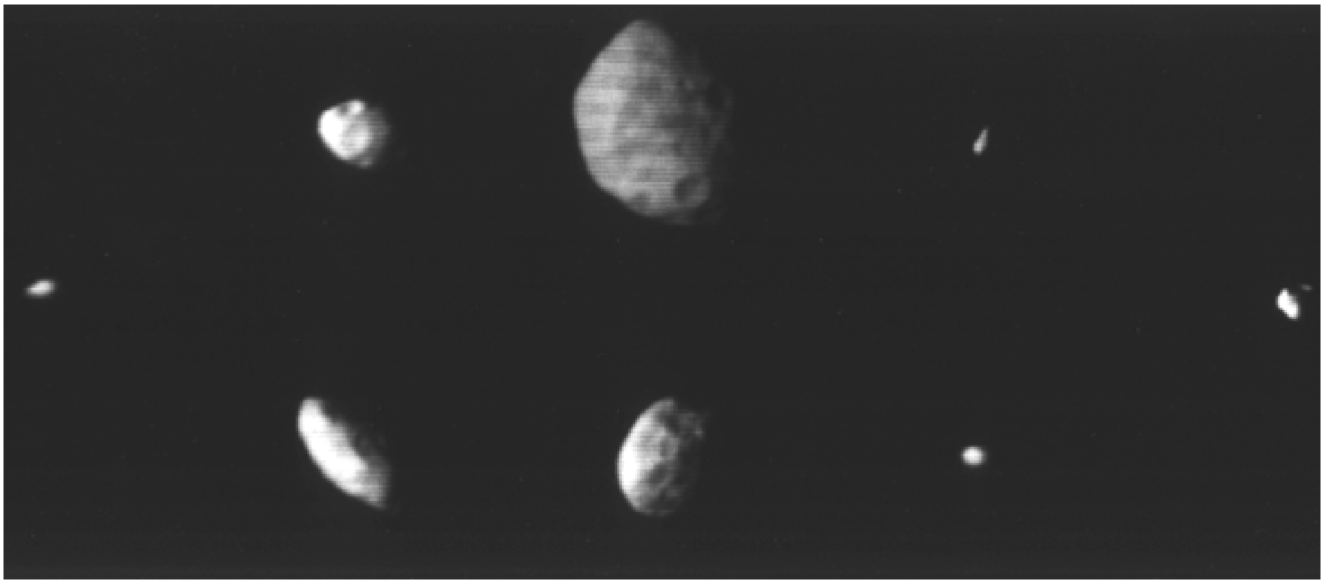
The two Voyager spacecraft provided the first detailed reconnaissance of the Saturn system. They provided the first evidence that the satellites had been geologically active after their formation and that one icy satellite, Enceladus, may be still active. There are significant gaps in our knowledge about Saturn's moons that can only be addressed by a more detailed observational plan and sophisticated instruments. The Cassini mission is designed to undertake this endeavor.

The Cassini payload represents a carefully chosen suite of instruments that will address the major scientific questions surrounding Saturn's moons, as follows:

First, what is the composition of the surfaces of these satellites? Although ground-based spectroscopic measurements showed water ice to be prevalent on their surfaces, the existence of additional volatiles, hydrates, clathrates and impurities is a critical factor in understanding the satellites' evolution. Because many impurities lower the freezing point of ice, their existence could provide an explanation for the satellites' activity. Hydrated ammonia, for example, could be the driver for activity on Enceladus and Dione, but its spectroscopic signature is so subtly different from water ice, that only close reconnaissance by Cassini's Visible and Infrared Mapping Spectrometer (VIMS) may be able to detect its presence.

In most cases, the satellites are too dim for detailed Earth-based spectroscopic studies. Much of the key spectroscopic evidence exists in the ultraviolet and 3–20-micrometer region, which is opaque to the terrestrial atmosphere. The nature of the dark material on the dark side of Iapetus, Hyperion, Phoebe and some of the small satellites is mysterious. Is it unprocessed and primordial? Is this material rich in organics and, as such, is it related to the origin of life? Is it similar to the dark material found on comets, some asteroids and other satellites in the outer solar system?

Next, what is the detailed morphology of the satellites, and what is the relationship between geological structures and compositional units? With a synergistic payload offering an Imaging Science Subsystem (ISS) that is capable of tens of meters resolution on the satellites and high-resolution spectrometers in the 0.055–1000 micrometer region — the Composite Infrared Spectrometer (CIRS), the Ultraviolet Imaging Spectrograph (UVIS) and the VIMS — and complementary radio-metric radar K_u-band measurements, it will be possible to correlate geological units with specific compositions.



The small satellites of Saturn. Clockwise from left: Atlas, Pandora, Janus, Calypso, Helene, Telesto, Epimetheus and Prometheus.

For example, what is the detailed distribution of dark material on Iapetus' craters, and what does that say about the origin of the material? Are the bright wispy streaks of Dione and Rhea rich in ammonia and thus plausibly formed from a hydrated ammonia slurry exuded onto the surface? What is the distribution of surficial impurities, and can they offer an explanation for the varying degrees of viscous relaxation on the satellites? Are the inner satellites coated with material from the E-ring?

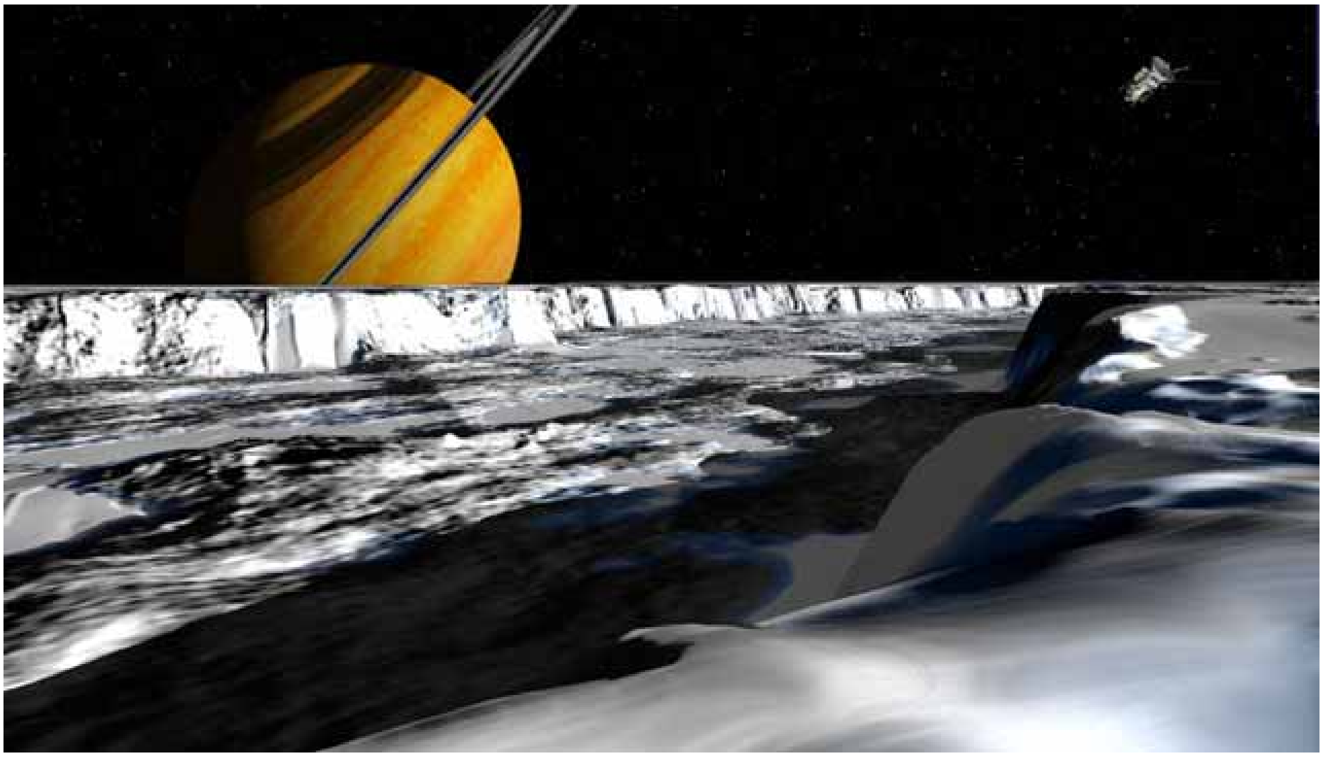
Third, are there compositional similarities between the rings, dust and some of the satellites, and if so, does that imply they are interrelated? Are the rings comminuted satellites? Do any of the dust or icy particles, which will be measured in detail by Cassini's Cosmic Dust Analyzer (CDA), appear to come from satellites? Is Enceladus the source of the E-ring?

Also, do any of the satellites have thin, tenuous atmospheres of molecular oxygen, OH or other material, similar to those recently found on Jupiter's moons Europa and Ganymede? Cassini's UVIS or possibly the ISS should be able to detect such atmospheres, which may in turn provide material to Saturn's magnetosphere. If there is significant erosion of material from the satellites' surfaces (or in the case of Enceladus, expulsion), the Ion and Neutral Mass Spectrometer (INMS), the CDA and the Radio and Plasma Wave Science instrument (RPWS) will study their composition, size and mass.

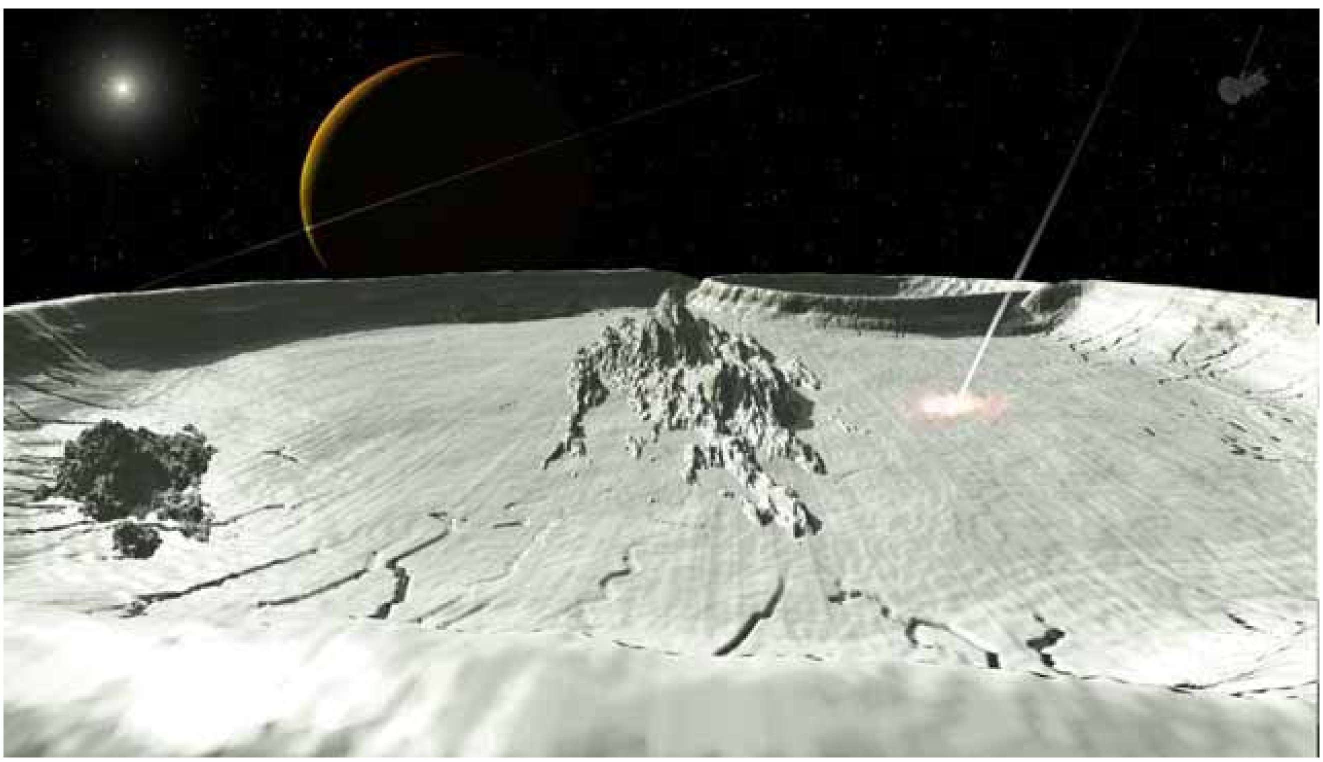
Fifth, are there any additional satellites? Are there any embedded in the ring system? How do these satellites interact dynamically with the rings? High-resolution imaging by the ISS will be able to detect kilometer-sized bodies and resolve the issue of 10 or so unconfirmed observations of additional satellites.

Further, what is the relationship between Saturn's magnetosphere and the satellites? Are the satellites a significant source of magnetospheric particles? Do any of the satellites have magnetic fields? Why does Dione modulate Saturn's radio emission? Is there a flux tube of some sort between the satellite and the planetary magnetic field? The Dual Technique Magnetometer (MAG), the Magnetospheric Imaging Instrument (MIMI), the Cassini Plasma Spectrometer (CAPS), the Ion and Neutral Mass Spectrometer (INMS) and the RPWS will be the key instruments for answering these questions.

Seventh, is Enceladus still active? High-resolution imaging by the ISS will detect any recent features, as well as geysers or plumes. Further compositional analysis of the plumes and deposits will help to determine the physical mechanism of the activity and its similarity to other activity on Jupiter's moon Io, Neptune's moon Triton and Earth.



Artist's conception of Ithaca Chasma, a huge trench on the moon Tethys.



This artist's rendition shows Saturn as it might appear from the surface of its second largest satellite, Rhea.

Then, what are the internal structures of the satellites? Did they fully differentiate? Close flybys of the satellites entailing precise measurements by the RSS of gravitational perturbations will be able to determine which satellites have cores. Accurate measurements of the density of each satellite, coupled with spectroscopically determined compositional information, will yield determinations of their bulk densities.

And finally, what was the origin of Phoebe? Is it a captured Kuiper Belt object or a more pedestrian asteroid? Is its surface material related to the dark material on either Iapetus or Hyperion?

With four years to investigate Saturn and its icy satellites, the Cassini–Huygens mission hopes to shed some light on the innumerable mysteries that remain about this solar system giant. Any answers that Cassini uncovers, of course, are equally likely to lead to even more questions.